The Development of a Full Architecture For High Performance Actuators For Navy Applications

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1. Purpose

The field of intelligent machines is on the verge of a revolution. A step towards this revolution is the development of the science and technology required for Power Electronic Building Blocks (PEBBs) developed by ONR as standard modules of increased performance and reduced costs for power distribution and control on-board ship. A similar need now exists for a Standard Actuator Building Block (SABB) to be the lowest level module to operate all systems (valves, ammunition handling, shipboard automation, aircraft fueling and re-supply, etc.) on-board ship. The goal here is to develop advanced actuator components (gear trains, internal sensors, prime movers, electronic controllers, standardized interfaces, etc.) to be embedded in a full architecture which is sufficiently flexible to be reconfigured on demand to provide maximum performance (high torque, precision, or stiffness), condition-based maintenance (when should a component be replaced) or fault tolerance (can the actuator recover from a fault even during operation).

In order to move towards this goal, multiple technical issues and challenges must be addressed and resolved. These issues include the following technical thrusts considered in the course of this proposal:

i. In-depth study of the literature
ii. Analysis of the science base for all component technologies
iii. Development of a full architecture concept using these components
iv. Modeling procedures for intelligent actuators
v. Acquisition methods for all modeling parameters
vi. Criteria development to evaluate performance of intelligent actuators
vii. Decision making procedures based on these criteria to maximize performance
viii. Development of performance maps and envelops for actuator operation
ix. Creation of the decision structure which permits condition-based maintenance
x. Development of a reconfigurable architecture to make recovery from faults feasible.

As indicated in the prior status report submitted in November 1999, the focus of current research efforts is upon the first seven of these ten issues. During the course of this project, these eight issues have been addressed in five major research reports culminating in five Master of Science degrees (all supervised by Dr. Delbert Tesar), awarded to the following five authors for the following research reports:

- Mr. Michael Bono – Advanced Sensor Technology for Industrial Actuators;
- Mr. Bulent Finci – Design of a Long Stroke Linear Actuator;
- Mr. Eric Hatcher - Conceptual Re-Design of an Advanced Switched Reluctance Motor for Direct-Drive Servo Applications;

- Ms. Chun Feng Huang – Architecture Development for the Actuator Management System Software; and
- Mr. Cameron Turner – Criteria Development for Actuator Resource Management.

Summaries of these reports are included in Section 2, including a listing of the critical sections of each document. A complete copy of each of these research reports is attached. The relationship of these reports to these technical issues is shown in Table 1.

Issue	1	2	3	4	5	6	7	8	9	10
Bono	•	•	•		•					
Finci	•	•	•							
Hatcher	•	•	•	•						
Huang	•	•	•				•			•
Turner	•			•	•	•	•			

Table 1: ***Research Report Contributions Relative to Technical Issues.***

2. Report Summaries

This section summarizes the attached documents, and indicates the critical sections in each document with respect to the previously identified technical needs of the project. The reports by Bono (Sensors), Finci (Linear Prime Movers), Hatcher (Rotary Switched Reluctance Prime Movers) and Huang (Software) all focus on component technologies necessary for intelligent actuators. The report by Turner (Criteria Development) provides the best overall view of an intelligent actuator.

2.1 Advanced Sensor Technology for Industrial Actuators

This document, by M. Bono, considers the requirements for a 10-sensor (position, velocity, acceleration, force/torque, current, voltage, magnetic field, temperature, sound and vibration) intended to support the operation of intelligent actuators. The requirements for intelligent operation provide a justification for the incorporation of perhaps 50 sensors of these 10 basic types.

The existing technologies that can be applied to produce sensors capable of meeting these requirements are reviewed, and necessary improvements are identified. On the basis of these technological capabilities, the requirements for this 10-sensor environment, and the commercialization potential of these technologies, preliminary specifications for the 10-sensor environment for an intelligent actuator are provided.

These sensors are developed for use in redundant resource allocation, nonlinear actuator modeling, multi-criteria decision-making, fault tolerance, and condition-based maintenance. One of the most significant proposals for these advanced sensors is the suggestion to include local sensor processing capabilities into the design of the sensor. This capability allows a sensor to self-calibrate, detect internal faults, compensate for sensor nonlinearities, and to reduce the noise in sensor signals by converting analog sensor data to digital data before transmitting that data to the actuator electronic control system.

Many of these concepts can be traced to the automotive and biomedical fields, which were considered in order to determine the commercialization potential for these technologies. This analysis suggests that the requirements for a 10-sensor environment within an intelligent actuator are technologically feasible and economically viable.

Chapter Content Summary:
Chapter 1 – Introduction
Chapter 2 – 10-Sensor Environment
Chapters 3, 4, 5 – Literature Survey
Chapter 6 – Sensor-Processor Integration Issues
Chapter 7 – Commercialization Potential
Chapter 8 – Future Research and Conclusions

2.2 Design of a Long Stroke Linear Actuator

This document, by B. Finci, develops a design for a long-stroke (~8 meter) linear actuator for a manufacturing cell application. However, much of the research is similarly applicable to the design of short-stroke linear actuators, which are useful for a wide variety of naval applications.

Multiple transmission designs are considered as candidates for this application, including a variety of rotary to linear drive systems. Preference was given to designs that are compatible with electromagnetic prime mover systems, as opposed to hydraulics, in order to facilitate a modular actuator architecture.

The selected design would incorporate a 10-sensor sensor array and incorporate and on-board actuator controller, support actuator intelligence, fault tolerance and condition-based maintenance, and would be capable of high performance in both the positioning and force domains. Additional technologies could be used to enhance the compensating control capabilities of the control system.

Chapter Content Summary:
Chapter 1 – Introduction
Chapter 2 – Comparison of Linear Actuator Technologies
Chapter 3 – Linear Actuator Architectures; Evaluation and Selection
Chapter 4 – Electromagnetic Design of a Linear Actuator
Chapter 5 – Mechanical Design of a Linear Actuator
Chapter 6 – Positioning Control of a Linear Actuator
Chapter 7 – Alternative Configurations
Chapter 8 – Future Research and Conclusions

2.3 Conceptual Re-Design of an Advanced Switched Reluctance Motor for Direct-Drive Servo Applications

This report by E. Hatcher addresses what is arguably the most critical component of an actuator, the prime mover. This subsystem is responsible for converting power into a force, torque or motion, depending upon the configuration of the subsystem. The capabilities of this system determine the capabilities of the actuator to produce an output, and determine many of the requirements for other subsystems, including the transmission, the sensors, and the electronic controller of the actuator.

One attractive alternative is to design an actuator without a transmission, resulting in a direct-drive actuator. Most current direct-drive systems are incapable of meeting the needs of high performance automation systems. This document pursues the design of a Switched Reluctance Motor (SRM) that is designed to meet the demands of high performance automation systems. The resulting design offers a 70% improvement over the state-of-the-art SRMs currently available, and a competitive advantage over other motor types.

This design was developed by pursuing a traditional design methodology. First, the needs of the customer were considered and used to define the requirements for the prime mover. These functional requirements are matched with component technologies leading to the development of a set of conceptual designs based on these component technologies. This set of conceptual designs is judged on the basis of a set of design criteria leading to the selection of a single concept for future refinement.

Chapter Content Summary:
Chapter 1 – Electromagnetic Motor Fundamentals
Chapter 2 – Review of Prior Designs
Chapter 3 – Customer Requirements for a SRM
Chapter 4 – Functional Analysis of an SRM
Chapters 5 and 6 – Conceptual Design and Concept Selection of an Advanced SRM
Chapter 7 – Future Research and Conclusions

2.4 Architecture Development for the Actuator Management System Software

This report, by C. Huang, addresses the intelligent management of an intelligent actuator, which is heavily dependent upon the development of software to support that intelligence. This software must operate in real-time, and should exemplify good software design principles including modularity and reuse whenever possible. Since one of the primary tasks assigned to the Actuator Management System Software (AMSS) is to process sensory information into the sensor reference model of an actuator, preliminary work on the software design focuses on the sensor module software.

While several methodologies and architectures exist for software design, few have gained the prominence of the object-oriented paradigm. This paradigm structures the software according to principles of inheritance, encapsulization and polymorphism. Extensive experience with object-oriented software design, layered software architectures and the programming language C++ led to the selection of these approaches to the design of the AMSS.

The AMSS was designed by utilizing the software architecture design method to translate system requirements into architectural specifications and then for the implementation of the sensor software module. The basic requirements for this system include high availability, modifiability, reconfigurability, fault tolerance, reusability and integrability. For the sensor module, sensor abstraction, signal processing, sensor fusion, and the sensor model reference requirements were all considered.

Chapter Content Summary:
Chapter 1 – Research Introduction
Chapters 2 and 3 – Software Literature Review
Chapter 4 – Architectural Development
Chapter 5 – Architectural Implementation for a Sensor Module
Chapter 6 – Future Research and Conclusions

2.5 Criteria Development for Actuator Resource Management

This report, by C. Turner, is concerned with the development of actuator criteria for use in managing the operation of a Redundant Actuator Model, or RAM. (As such, it provides the best overall view of an intelligent actuator.) The RAM utilizes four independent prime movers, each operating at different motion scales in order to produce an output motion that is beyond the capabilities of a single actuator. The RAM is comprised of two electromagnetic prime movers (100% and 10% motion scales), a piezoelectric prime mover (1% motion scale), and a magnetostrictive prime mover (0.1% motion scale).

This document surveys more than two decades of research conducted by the Robotics Research Group (RRG) as well as the applicable research conducted by the research community. Utilizing the definition of system performance developed by Hill and Tesar [1997] that defines system performance as "the ability for a system to reach and maintain a position," a definition of actuator performance is proposed and validated through the use of a Certainty Analysis methodology.

An analysis of an actuator system demonstrates that the performance of the system is determined by the system hardware, the predictive (feedforward) elements of the control system, and the compensating (feedback) elements of the control system. Performance enhancements to any of these components improve the performance of the system as a whole.

The ten performance criteria defined in this report enhance the performance of the predictive control system, and thereby the performance of the actuator system. In addition, six operational criteria defined in this report allow for the operation of redundant actuator systems. While the operational criteria do not enhance the performance of the actuator in terms of its output position, force or torque, these operational criteria allow an actuator to use redundant resources to perform tasks that it could not otherwise perform, thus enhancing the performance of the actuator system. This duality in performance also appears in redundant robotic systems.

In addition, information from the experiments conducted to verify the validity of the performance criteria in simulation was used to estimate the significance of the different nonlinearities. These experiments predict that effectively modeling saturation is of crucial importance in high performance actuators. Utilizing all of this information, several proposals are made for further work on intelligent actuators.

Chapter Content Summary:

Chapters 1 and 2 – Literature Survey
Chapter 3 – Certainty Analysis; Actuator and System Performance Relationship
Chapter 4 – Redundant Actuator Model; Criteria Development; Control System Performance Contribution
Chapter 5 – Criteria Performance
Chapter 6 – Nonlinearity Significance; Future Research on Nonlinearities
Chapter 7 – Future Research and Conclusions

3. Summary Assessment

The engineering team at the RRG has completed an assessment of potential sensor technologies, rotary and linear prime mover technologies, justified the need for additional intelligence within high performance actuators, and have developed a software architecture and associated performance and operational criteria to support the development of truly intelligent actuator modules.

This research was conducted as part of a one-year effort to lay the groundwork for the scientific development of advanced intelligent actuators to meet Navy application requirements. The Statement of Work from the original proposal suggested that the necessary tasks involved include:

i. In-depth study of the literature
ii. Analysis of the science base for all component technologies
iii. Development of a full architecture concept using these components
iv. Modeling procedures for intelligent actuators
v. Acquisition methods for all modeling parameters
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Five students pursued these tasks, with partial funding from ONR under a Basic Science Grant. The results of their research culminated in five Master of Science Theses. Copies of these five research reports are appended to this document, or are available on the Sponsors Section of the Robotics Research Group Website (http://www.robotics.utexas.edu) via the username: *doeuser* and the password: *oppenheimer2000*. Table 1 categorizes these contributions with respect to the ten tasks identified in the original Statement of Work.

4. Major Accomplishments and Highlights of This Research

- Identified potential sources of technical information
- Conducted an assessment of sensor technologies
- Preliminary Development of the Specifications for a 10-sensor architecture to support actuator intelligence
- Conducted an assessment of rotary and linear prime mover technologies
- Produced a design for a Switched Reluctance Prime Mover for rotary actuators, and a design for a Long-Stroke Linear Actuator
- Developed a linear Mathematical Model to predict the performance of the Switched Reluctance Prime Mover Design
- Developed a software architecture to support high availability, modifiability, reconfigurability, fault tolerance, reusability and integrability demands.
- Justified the incorporation of intelligence in advanced, high performance actuators
- Developed 10 Performance Criteria, 6 Operational Criteria, and reformulated 10 additional Performance Criteria to support intelligent actuator operation
- Developed a Conceptual, Mathematical Model of a Four-Layer Redundant Actuator simulating intelligent operation
- Developed a Software Architecture to support intelligent actuator operation
- Identified important areas for further technical research

5. Conclusions

The research conducted under the auspices of this ONR Research Proposal represents a significant foundation for the development of high performance actuator systems. Collectively, this research addresses several major component technologies (Prime Movers, Sensors, and Software) within the actuator, as well as providing a foundation for the development of multi-criteria decision-making techniques to support actuator intelligence. Together, these technologies merit consideration for continued development and eventual inclusion in the development of SABBs to support future naval demands for high performance automation systems. Notably, while all of these reports describe promising technologies and approaches to the challenges facing automation systems, further research is required in numerous areas to realize their full potential as deployable components.

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